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The critical period for language acquisition is often explored in the context of second language acquisition. We focus on a crucially different notion of critical period for language, with a crucially different time scale: that of a critical period for first language acquisition. We approach this question by examining the language outcomes of children who missed their critical period for acquiring a first language: children who did not receive the required language input because they grew in isolation or due to hearing impairment and children whose brain has not developed normally because of thiamine deficiency. We find that the acquisition of syntax in a first language has a critical period that ends during the first year of life, and children who missed this window of opportunity later show severe syntactic impairments.

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The critical period for language acquisition is often explored in the context of second language acquisition. Most studies and theories of the critical period for language ask until when children and adolescents can acquire a language effortlessly and accurately like a first language, given that they have already been exposed to a first language, and acquired it (or started acquiring it). This question received various ages as an answer, mostly revolving around puberty ages.

In this review, we focus on a crucially different notion of critical period for language, with a crucially different time scale: that of a critical period for first language acquisition. We will approach this question by examining cases of children who missed their critical period for acquiring a first language: children who did not receive the required language input or did not have the required brain structures during the critical period for first language acquisition, and the way it affected their later language development. Several researchers suggested that there are critical periods with different time frames for different language abilities [1•,2••,3,4•]. We bring some evidence for the domain-specificity of the critical period for language, and focus on the critical period for the acquisition of syntax.

The first theory regarding critical period for language was suggested by Penfield and Roberts [5•] and later developed by Lenneberg [6••]. According to Lenneberg's theory, natural acquisition of (a first or a second) language from mere exposure occurs during a critical period that begins at the age of two years and ends in puberty. The revolutionary idea behind this critical period hypothesis was that there is a period in which language is acquired more naturally and accurately, and this period has a certain onset and offset. According to Lenneberg, the critical period for language begins after a certain maturation of the brain, and ends with a certain loss of cerebral plasticity. Lenneberg and other researchers who tested the ages in which a child can still acquire various aspects of a new language reached various ages, all around puberty [7•]. Later studies contested this time frame: the onset of two years of age was refuted by a myriad of behavioral and structural studies showing that a large chunk of language is already acquired by the age of two years, and that, in fact, children acquire certain aspects of language already in the first days of life and even in uterus [7•,8–13]. Mehler *et al.* [11] found that neonates show a preference for languages they heard *in utero*. Querleu *et al.* [9], Nazzi *et al.* [14], Dehaene-Lambertz *et al.* [15], and Dehaene-Lambertz and Pena [16] found that neonates in their first few days can discriminate between languages belonging to different rhythmic families, and exhibit sophisticated speech perception capacities, such as phoneme categorization and identification of abstract phonemes. Nazzi and Ramus [17] showed that four months old infants can already distinguish their native language from a rhythmically similar one. Various studies also show that the offset suggested by Lenneberg is too late. Even around the age of four years, some aspects of a second language are not acquired as native anymore, and the acquisition already resembles that of adults who acquire a second language (see [2••] for a review).

One of the questions that researchers find intriguing until this day is why this critical period ends. This question is, in effect, two questions: one is which changes in the brain cause the critical period to end, the other is what is the functional role of such offset. As to the neural underpinnings for the offset of the critical period, Lenneberg ascribed this loss of plasticity to the completion of the 'lateralization of language functions', in which one of the hemispheres (usually the left) becomes more dominant for language. Lenneberg's explanation (or time frame) was criticized by researches who asserted that lateralization is completed much earlier, before the age of five years [18•,19]. Other studies, done mainly in connection to the development of the visual system [20–23], suggested that the onset and offset of a critical period is contingent upon the excitatory–inhibitory balance of neurotransmitters in the brain: brain activity in young infants is mostly excitatory, with neurotransmitters excreted in the synapses mainly intensifying the electrical brain activity. Gradually, inhibitory neurotransmitters come into play. According to some researchers [20–26] the balance between the excitatory and inhibitory activity defines the critical period (for review, see [4•]). The suggested molecular mechanism that affects the critical period is different for each stage: onset, plastic period, and offset. The onset is attributed to molecular triggers that can shift neural circuits from an immature to a plastic state. The neural circuits using the neurotransmitter gamma-aminobutyric acid (GABA) are crucial for the onset of the critical period [20]. During the plastic period, some molecular factors enable changes in neural circuits in response to sensory experience [4•]. Finally, the offset is defined by molecular brakes, both physical obstacles that physically prevent synaptic pruning and outgrowth (such as PNN and myelin-related signals), and functional mechanisms (such as Lynx1, serotonin reuptake), that dampen the neuromodulatory systems regulating acetylecholine and serotonin, which prevent further structural changes, limit excessive circuit rewiring, and shift the neural circuit to a stable state (see [4•] for a comprehensive review).

As for the functional advantage of such offset, theorists suggest that an expiration date on a critical period is required to help keeping the structure that has already been learned, and allow for its consolidation and stabilization. Under this view, the loss of plasticity has evolved to occur after a language has been acquired. As Pallier [27•,28••] notices, this suggestion is still open to two interpretations: loss of plasticity after each individual has gained the necessary body of knowledge, or loss of plasticity as an outcome of brain maturation, which occurs at a point where most of the individuals of this species have already completed their language acquisition mission. The first interpretation is consistent with a theory that proposes that language acquisition of the individual affects the loss of plasticity [27•,28••,29]. The second might be attributed to maturational factors [27•,28••]. As we show below, this question has an empirical answer from the study of children who did not complete acquisition during the relevant period.

Importantly, most of the studies of a critical period for language acquisition tested the acquisition of a second language given that one language has already been acquired. We suggest that a critical period for acquiring a first language has crucially different and earlier time line, which for the acquisition of syntax is the first year of life, and that it takes two for the tango of first language acquisition: a neurologically prepared mind, and sufficient language input.

Since his early writings, Chomsky stressed the contribution of two factors to the proper acquisition of language: a language acquisition device — an innate, neurologically wired, mechanism that specifies which rules are possible in human languages, and language input. Both these factors, he suggested, are crucial for the development of normal language, and the innate mechanisms require appropriate stimulations to become activated [30]. Below we present studies that indicate that language input is indeed crucial for normal acquisition of a first language, and specifically of syntax in the first language, and that the exact timing during the child's development in which this language input is provided is also crucial. Language input that arrives only after a certain critical period has ended may be too late to allow for normal language development. This crucial role of input can be seen in studies of two populations: children who grew in isolation, without proper human language input, and children who were born with hearing impairment (and to a non-signing environment), and therefore their language input was reduced during a certain period of time until they received hearing devices.

Isolated and feral children: insufficient language input

Several cases of children who grew in isolation and experienced drastic deprivation of language input during the critical period for first language acquisition are reported in the literature. These children later failed to acquire language even after exposure to language and sometimes formal language teaching, and their main domain of difficulty was morpho-syntax [31]. The case of Genie is one known example for impaired language acquisition following deprivation of language input during a critical period. Genie was kept in isolation since the age of 20 months until she was 13;9 years. All through this time, and possibly also before the age of 20 months, she has barely been spoken to [32••,33]. Genie did not speak at all when she was discovered. In the following months, she did acquire some language, but the process was slow and inefficient.

Whereas her vocabulary consistently grew, Genie failed to develop normal syntax. Her speech contained no question words, no demonstratives, and no particles. Genie also failed to construct sentences derived by syntactic movement [32••,33]. This demonstrates a crucial point regarding critical periods for first language acquisition: different language domains may show different acquisition paths, with different critical periods [1•,2••], and some may not be constrained by critical periods at all. Syntax, and specifically syntactic movement, are affected by lack of language input early in life, whereas single lexical items may still be acquired once language exposure begins or resumes.

Genie's language was thoroughly studied (see also [33,34•,35–39]). Not all later studies of isolated children explored various domains of their language and specifically syntax, but the pattern seems to be similar: whereas single words can be acquired later in life, syntax can no longer be acquired normally [1•,31,34•,40–44].[1]

This suggests that language input during the early years if life is crucial for the development of syntax. What is the time frame of this critical period for syntax?

Children with hearing impairment: insufficient language input

Another very strong evidence for the crucial role of language input in early ages, which provides specific information about the time span of the critical period for the acquisition of syntax in the first language, is that of children with hearing impairment. Children who were born with hearing impairment to an oral-language-speaking environment, and were raised without sign language, do not receive sufficient language input until they are provided with hearing devices: hearing aids or a cochlear implant. Many of these children show syntactic impairments [49–52,53••,54•,55–61,62••,63].

Importantly, not all hearing-impaired children show language difficulties: some of them develop normal language and normal syntax. Congenitally hearing-impaired children form a very heterogeneous group. These children differ in factors such as degree of hearing loss, type of hearing device (hearing aids or cochlear implants), and the age in which they started receiving language treatment. Of these background factors, the age at which these children started receiving language input emerges time and time again as the one factor determining the language outcome. In deaf children born to deaf families, the language input is provided since birth as sign language. Studies show that deaf or hearing children who acquire sign language from their deaf parents experience normal language development [64•,65,66,67••]. This is not the case of deaf children born to hearing families. In this group, the age of first language input, and thus the language outcome later in life, is highly depended on the age in which they received hearing devices.

To examine this point, Szterman and Friedmann conducted a line of studies of orally trained children with hearing impairment, focusing on a very specific (and vulnerable) syntactic ability — the comprehension and production of sentences derived by syntactic movement [52,53••,54•,55–57,60,61,62••]. Namely, the ability to understand and produce sentences in which the word order is not the canonical one. They found that many children with congenital hearing impairment show difficulties understanding and producing relative clauses, such as '*This is the girl that the grandma drew*', and Wh-questions such as '*Which girl did grandma draw*?', where the theme of the action follows the agent. Friedmann and Szterman's studies showed that the crucial factor determining whether or not a school-aged child can have normal comprehension and production of sentences with movement was whether or not s/he had a hearing device fitted before age eight months. Namely, of all the children who have binaural hearing impairment from birth, only those who receive language input during the first year of life may later develop normal syntax (fitting a hearing aid does not always guarantee that the language input will be received, and hence, does not always result in good syntax, as sometimes children do not benefit from some types of hearing devices).

Other background factors such as degree of hearing loss and type of hearing device did not seem to affect syntactic performance. These findings suggest that the critical period for syntax in the first language ends earlier than assumed, during the first year of the child's life. If language input is not available during this time period, this may have severe and far-reaching implications for the syntax of this individual later in life.

The crucial role of the availability of language input during the first year of life can be seen in another type of finding: children who lost their hearing after their first year of life and children whose hearing loss was only monoaural were found to show normal syntactic abilities [68]. Namely, it is not the hearing loss *per se* that causes syntactic impairment, but rather whether or not language input was received during the first year: children who did not receive language input during the first year were impaired,[2] whereas children

[1] The lack of input during an early critical period for syntax acquisition may also underlie consistent reports of language and syntactic difficulties in children who were adopted after age one or two years [45–48]. In these cases, many reasons can underlie language difficulties, but in some of the cases, it might be that these adopted children have language impairments because they were brought up in orphanages in which they did not receive enough language input, and are adopted after the window of opportunity of the critical period has closed.

[2] Even temporary hearing loss during the critical period for first language can give rise to language problems. For example, children whose language input during the first 18 months was limited by ear infections and fluids in the ear (otitis media with effusion) were found to be in greater risk of language difficulties [69,70].

who were hearing-impaired during the first year but received input thanks to a hearing device, and children who received normal input during the first year and lost their hearing later can show normal syntactic development.

Other studies, which tested language in general but not syntax specifically, also found that the most important predictor for normal language development is the age of identification of the hearing loss and age of initiation into intervention services: a line of studies by Yoshinaga-Itano [71•,72,73••,74,75] concluded that the age of six months is the drainage divide between the later development of normal and impaired language. Moeller [76] found that children enrolled in intervention before age 11 months had better vocabulary scores at age five years than those who were enrolled during their second year of life. Mayberry and her collaborators systematically tested syntactic abilities in sign language and in a second language, English, in deaf individuals who were exposed to sign language and to English in various ages. They showed unequivocally that the age at which a child is exposed to a first language affects the proficiency in both first and second language [66,67••,77,78]. Similarly, Cormier *et al.* [79] found that native signers of BSL were more accurate in grammaticality judgment in BSL than speakers who acquired BSL between two and eight years of age.

The importance of language input during the first months of life for the developmental of complex syntax might seem surprising given that in this time children do not seem to be able to say or understand sentences. Some studies suggest that the syntactic learning during the first year is derived from other linguistic abilities that are already present during this time, such as prosody [80], phonology [81], and word frequency [82].

The findings about critical period for syntax acquisition in children with hearing impairment shed further important light on the bases for the ending of the critical period: one approach is that brain maturation is responsible for the ending of the critical period, the other is 'the uncommitted cortex' approach suggested by Penfield and others, according to which once input is given, the brain closes the gates of acquisition in order not to harm the acquired grammar [27•]. The data from children with hearing impairment seem to vote in favor of the brain maturation approach. Namely, it might be that the brain has evolved to close off the acquisition process at some point in order to preserve the already-acquired grammar, but currently, the critical period for first language seems to finish at a certain age whether or not the necessary grammar has been formed. This is clearly seen from the fact that the deaf children who did not receive input still missed the critical period train. The mechanism of the effect of lack of input of deaf children during the first year of life may either result from the critical period ending before enough input has been received, or because the critical period has not even started, because language input is required to ignite this process (Dehaene-Lambertz, p.c.).

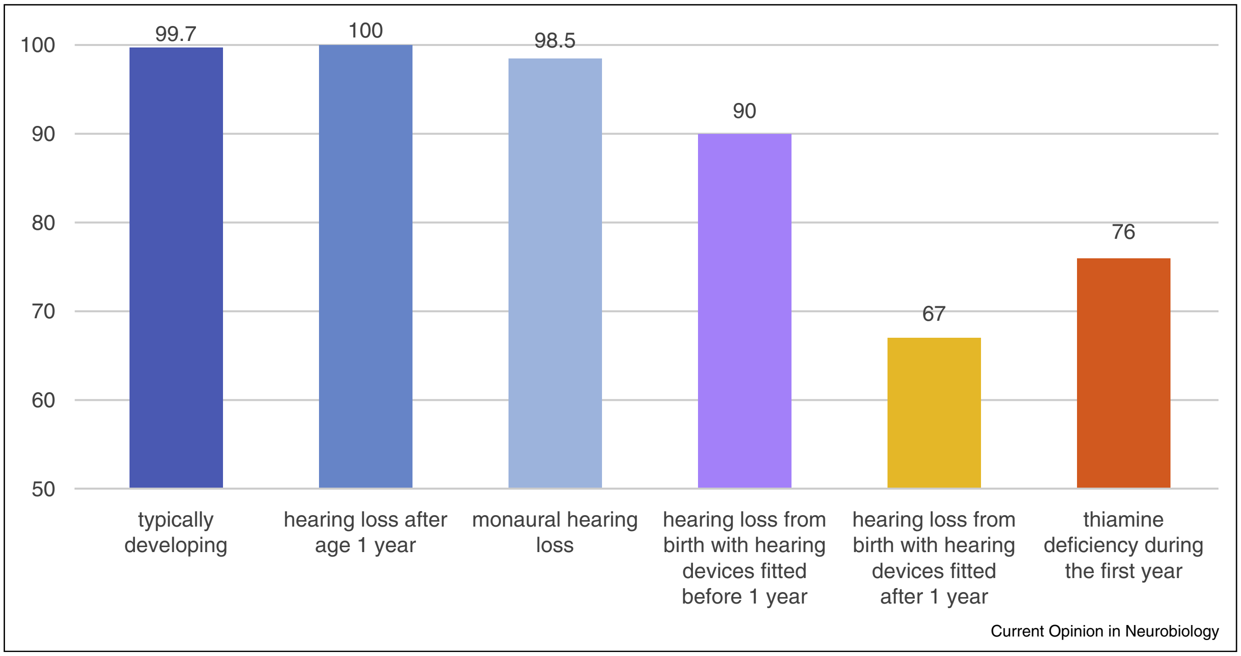
Thiamine deficiency during the first year

Until now we have discussed infants who have not received the relevant language input during the first year of life, the critical period for a first language. The significance of the first year of life for the normal development of syntactic abilities is also seen in a completely different population — individuals whose brain structures that are supposed to support the acquisition of syntax are affected by lack of crucial micronutrients during the first year of life. Fattal *et al.* [83••,84] tested the language abilities of children who suffered from a deficit of thiamine, a vitamin necessary for brain development, during the first year of life due to the consumption of a thiamine-deficient milk substitute. Fattal *et al.* found that these children showed severe syntactic difficulties when they were five and nine year olds. Even though the children received thiamine again after several weeks or months, this was too late: the children who experienced thiamine deficiency during the first year of life were later unable to develop normal comprehension and production of syntactic structures derived by syntactic movement such as Wh-questions, object relative clauses, and topicalized sentences. When these children were tested around age nine, almost all of them (56 of 62 children tested) showed impaired syntax, but 21 of the 56 syntactically impaired children had normal lexical retrieval, and 33 of them had normal phonological abilities (or at least normal ability to repeat words and nonwords). These differences between different types of language abilities indicate once again something very important about the critical period for language acquisition: that in fact, there are different critical periods for different language domains. Like in the case of Genie, the thiamine-deficient children were later able to acquire new lexical items, and develop the process of lexical retrieval despite the thiamine deficiency during the first year of life, but were no longer able to recover, after the loss of plasticity, from their syntactic impairment.

Pharmacological hope

Is the loss of plasticity irreversible? Recent studies use the excitatory–inhibitory balance theory discussed above to try and manipulate critical periods in pharmacological ways [22,23,85,86]. For example, studies revealed that the anti-depressant SSRI (Selective Serotonin Reuptake Inhibitor) Fluoxetine (Prozac) can restore the ocular critical period in rats [87]. It was suggested that the revival of ocular plasticity was achieved by the effect of Fluoxetine on the excitatory–inhibitory balance. SSRIs were also found to affect motor recovery [85]. In the language domain, a study on the development of phoneme discrimination even found that children whose mothers were using SSRIs during pregnancy showed accelerated phonemic perception [86]. Other studies showed reopening of the critical period by Genetic removal of Lynx1 or

Figure 1



The comprehension of structures derived by Wh-movement (object relatives, object questions, and topicalization), in a sentence–picture matching task in various groups differing on language input and brain development during the critical period for the acquisition of syntax in a first language: the first year of life.

acetylcholinesterase inhibitor treatment in animals (see [4•] for a review). In the case of language, and especially syntax, animal models cannot provide an answer, and the specific effect of pharmacological intervention on critical periods for first language acquisition, and specifically on syntax, is yet to be investigated.

Epilogue

Language input and a neurologically prepared mind are the essential tandem for the acquisition of syntax in a first language. If language input is not available or when micronutrient deficiency block brain development during the first year of life, the syntax does not develop normally, and children and adults may fail to understand and produce sentences with complex syntax in their first language (see Figure 1). Knowing the influence of the first year of life on syntax is not only important for the understanding of the mechanism of language and language acquisition, but also has direct clinical implications. These findings should raise awareness and dictate action with children, immediately upon detecting they have a hearing impairment, as it is crucial to provide language input as early as possible. The very early offset of the critical period for syntax in the first language also bears on a much wider population, as this lack of input can also result from temporary hearing loss, as in the case of ear infections and fluids in the ear, which, when present for a significant time during the critical period can affect language outcome. In a similar way, the findings about the role of thiamine during the critical period for language acquisition might have implications on the syntactic abilities of many people around the world, ranging from individuals with specific food intolerance or whose mothers suffered malnutrition or were in a thiamine-deficient diet during pregnancy, to populations who suffer from malnutrition. Thus, there is hope for pharmacological effects that may re-open the critical period for language for those who missed their critical period, but awareness might prevent children from missing their critical period, and hence prevent future language deficits.

Conflict of interest statement

No possible conflicts of interest exist for any of the authors.

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